Hydrogen Production and Utilization

A Canadian Perspective - Sam Suppiah

Canadian Nuclear Laboratories, Chalk River, Canada

Pathways to Decarbonization: An International Workshop to Explore Synergies Between Nuclear and Renewable Energy Sources

National Renewable Energy Laboratory, Golden, Colorado

2016 Jun 9-10

Presentation Outline

- Introduction
  - Hydrogen demand
  - Hydrogen & Canada
  - Hydrogen for transportation
- Hydrogen Production and Utilization at Canadian Nuclear Laboratories (CNL)
  - Hydrogen Production from Nuclear Technology
  - Hydrogen Utilization
- Hydrogen Energy Storage
- Energy Scene in Canada – Nuclear and Renewables

Hydrogen Demand

- **Current world demand for H_2 : ~50-60 Mt/a (increasing rapidly – USD 118B in 2016 to 152B by 2021)**
  - **Ammonia production 40 – 45 Mt/a**
  - **Methanol 1 – 2 Mt/a**
  - **Oil refining 10 – 15 Mt/a (growth area)**

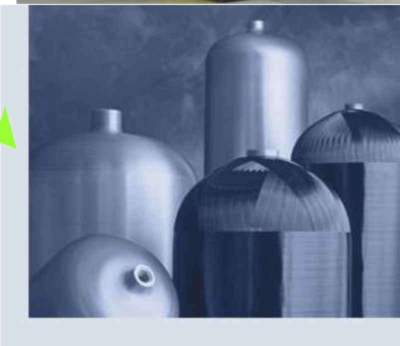
- **H_2 used for synthetic crude upgrading (Canada)**

  (2.4 – 4.3 kg H_2 per barrel of bitumen)
  - **Current: 2.0 Mt/a**
  - **By 2020: 6.0 Mt/a (?)**

- **Hydrogen as a transportation fuel**
  - **? Mt/a**

Hydrogen & Canada

- Canada has been a leader in development of hydrogen technologies stretching back for decades. Among best known:
  - Ballard (PEM fuel cells)
  - Hydrogenics Energy Systems
  - Dynatek Industries (high-pressure storage tanks)



- Canada is also a huge hydrogen producer/consumer
  - Nearly three million tonnes of hydrogen per year
    - one-third of the United States' production
    - largest per-capita hydrogen producer in the OECD
    - Oilsands projects are voracious consumers of hydrogen

Hydrogen for Transportation

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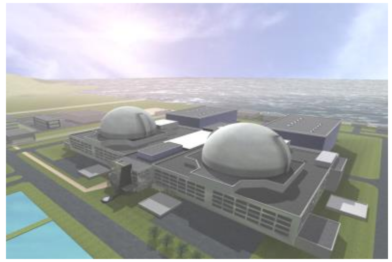

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Uranium Mining | **CANDU & SCWR** | **Electrolysis** | **Distribution System**

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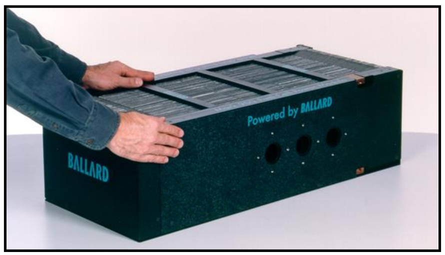

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Power for hydrogen vehicles that could replace many gas burning vehicles in Canada & elsewhere

Fuel Cells

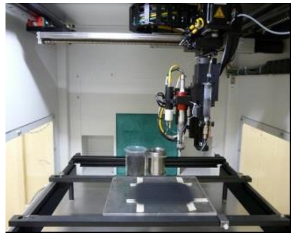
With the benefit of no carbon dioxide emissions!

Innovative Environmental Solution

Hydrogen Production & Utilization at CNL

Catalyst Production

- Fuel cell
- Electrolysis cell
- Hydrogen Safety Systems
- Hydrogen Isotope Exchange
- Dissolved Oxygen Removal
- Hydrogen Purifier

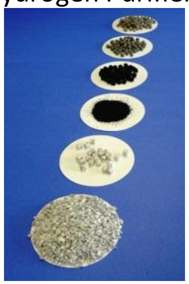


Programmable X-Y-Z-Θ Spray Coating Machine

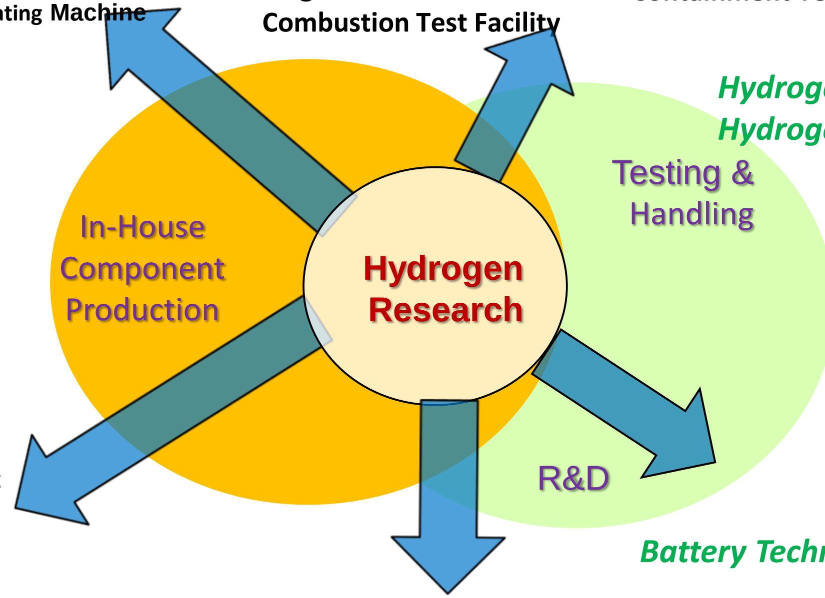
Large-Scale Vented Combustion Test Facility

Containment Test Facility

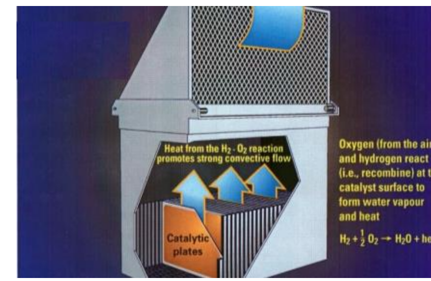
Winnipeg Transit Garage

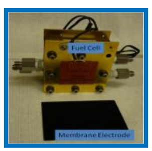


Hydrophobic Screen Catalyst



Hydrogen Safety Systems – Catalytic Hydrogen Recombiners





Fuel Cell Catalyst

PEM Electrolyser Catalyst

Battery Technologies

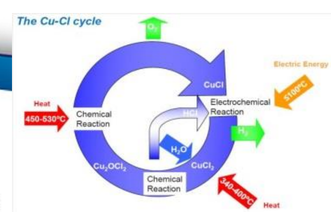
Fuel Cell Test Stations

Membrane and Membrane Electrode Assembly

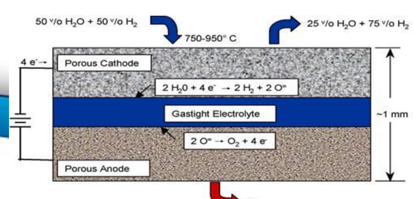
- Fuel Cell
- Electrolysis Cell
- Radiation Resistant

Casting Table & Oven for Membrane Production

Hydrogen Production – Nuclear & Renewable



Copper-Chlorine Thermochemical Cycle



High Temperature Steam Electrolysis

Metal Evaporator

Hydrogen from Nuclear Technology

- **Central Issues:**
  - **Is it price competitive?**
    - ✓ **Current status - must use intermittent production at off-peak electricity prices**
    - ✓ **Fits well with nuclear base-load operation**
  - **Will the price be stable?**
    - ✓ **Yes**
  - **Is it environmentally friendly?**
    - ✓ **Avoids 8 kg CO_2 per kg of H2 produced (compared to Steam Mathane Reforming)**
    - ✓ **One 250,000 bbl/d upgrader –save 2.5 Mt CO_2/a**
  - **Can production achieve continuity of supply?**
    - **H_2 storage in underground caverns**
    - **ICI has used caverns at Teesside UK for 30 years**
    - **embed in a large supply network**

Current Nuclear Hydrogen Production Option

- **Low Temperature Electrolysis - Off-peak electricity storage scenario**

    - Nuclear plants are not designed to load-follow, storage helps in maintaining base-load operation

    - Improves economics of nuclear plant operation

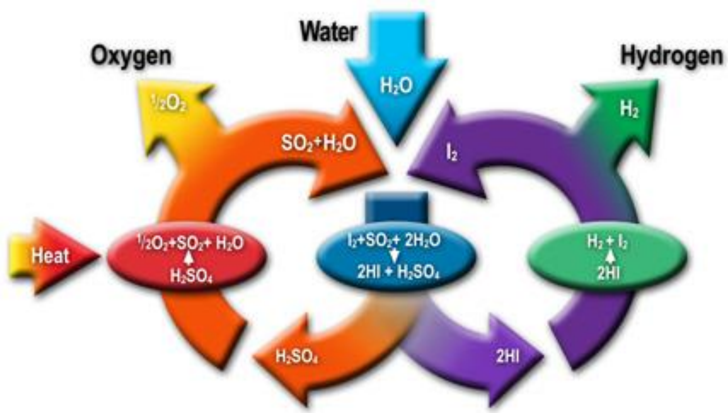
    - Provides large-scale electricity storage capacity

    - Two marketable products: hydrogen and electricity

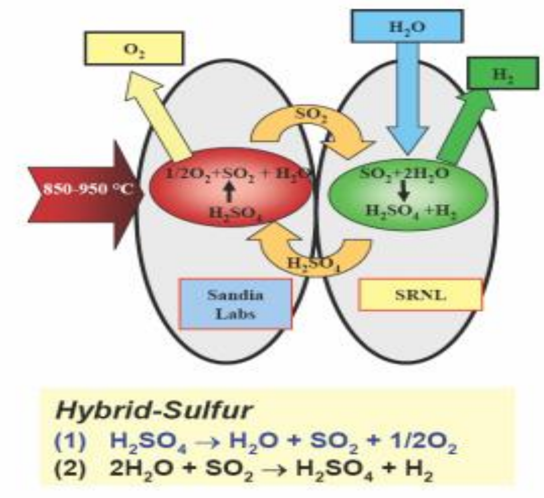
Next Generation Nuclear Hydrogen Production Options (also suitable for integration with Solar)

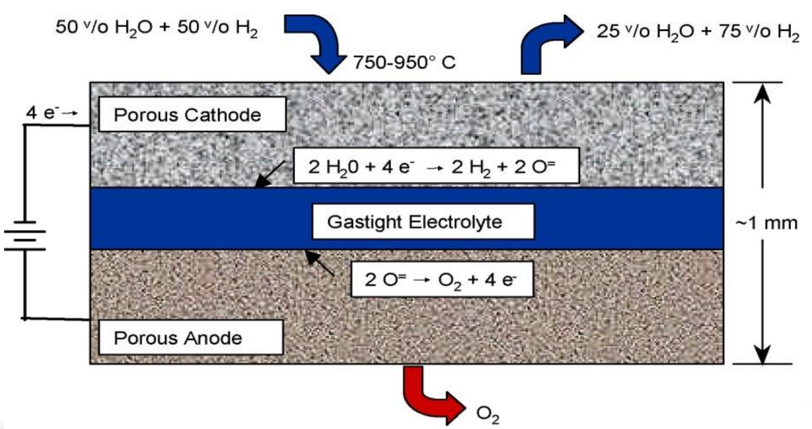
- High Temperature Steam Electrolysis (HTSE)
  - Suitable for integration with Moderate Temperature & High Temperature Nuclear Reactors
  - CO2 co-electrolysis to produce CO+H2 (synthetic gas)
- Thermochemical Cycles
  - Sulphur-Iodine (S-I) Process
    - Need Very High Temperature Reactor (Japan, Korea, China, India & others)
  - Hybrid Sulphur (Hyb-S) Process
    - Need Very High Temperature Reactor (US?)
  - Copper Chlorine Process
    - Moderate T Reactors (SCWR, Liquid Metal Reactors, Molten Salt Reactors)
    - Being developed in Canada for integration with Super Critical Water Reactor

Next Generation Nuclear Hydrogen Production Options

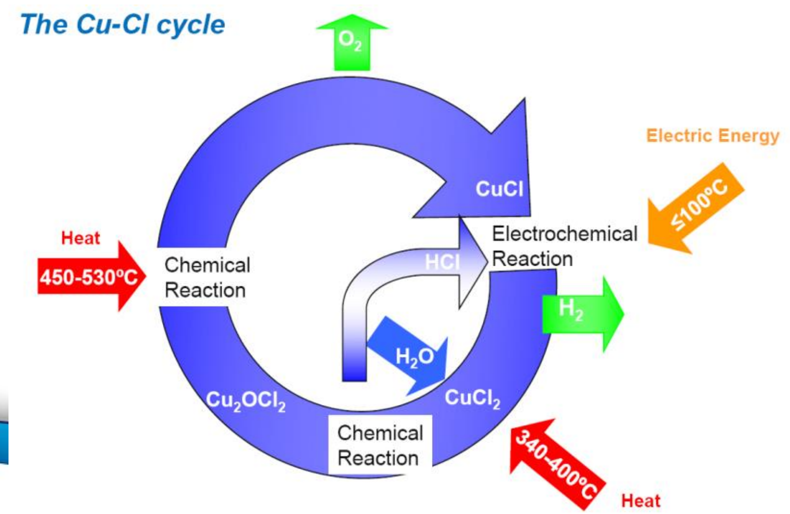


Sulfur-Iodine Process





High Temperature Steam Electrolysis



Attractiveness of Cu-Cl Cycle

- High efficiency (from Scoping Flowsheet Methodology) - 41%
- Low temperature requirement for heat source <530°C
- Temperature requirement for heat source met by currently existing power plant technology (e.g. thermal stations using supercritical water cycles) – BOP technologies exist
- Materials-of-construction and corrosion issues more tractable at 500°C than at higher temperatures required by other cycles
- Inexpensive raw materials as recycle agents (for example, compared to iodine for S-I cycles)
- No requirement for catalyst in thermal reactions

Canadian and International Collaborators

Canadian Nuclear Laboratories (CNL)

University of Ontario Institute of Technology (UOIT)

- Faculty of Engineering and Applied Science
- Faculty of Science
- Faculty of Energy Systems & Nuclear Science

University of Toronto

University of Guelph

University of Western Ontario

University of Waterloo

McMaster University

Argonne National Laboratory

Pennsylvania State University

University of Maribor

Czech Academy of Science

Ontario Power Generation

Regional Municipality of Durham

Marnoch Thermal Power Inc.

Phoenix Canada Oil Company Ltd.

Generation IV International Forum

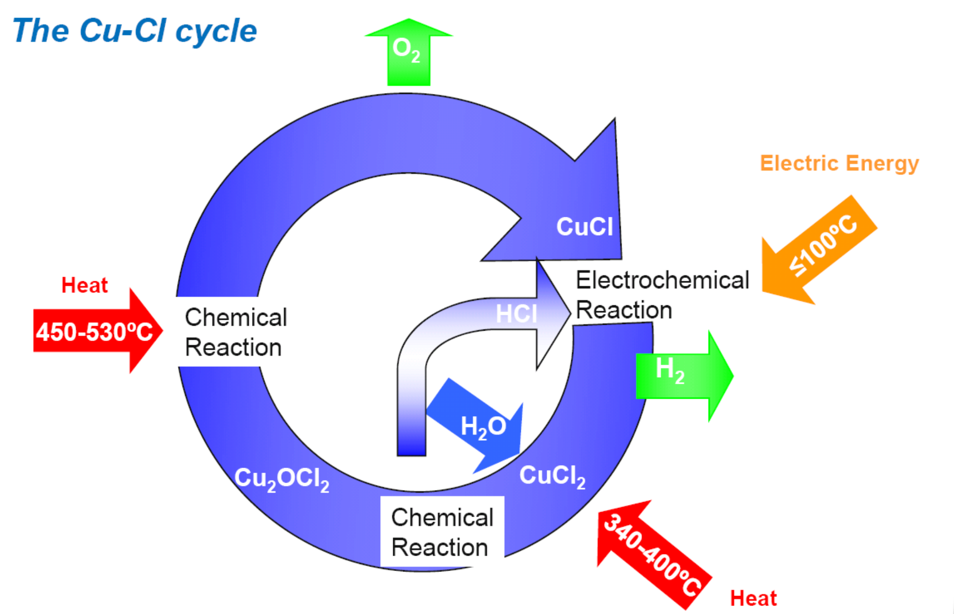
International Nuclear Energy Research Initiative; I-NERI

University Network of Excellence in Nuclear Engineering; UNENE

Copper-Chlorine Thermochemical Cycle (Cu-Cl)

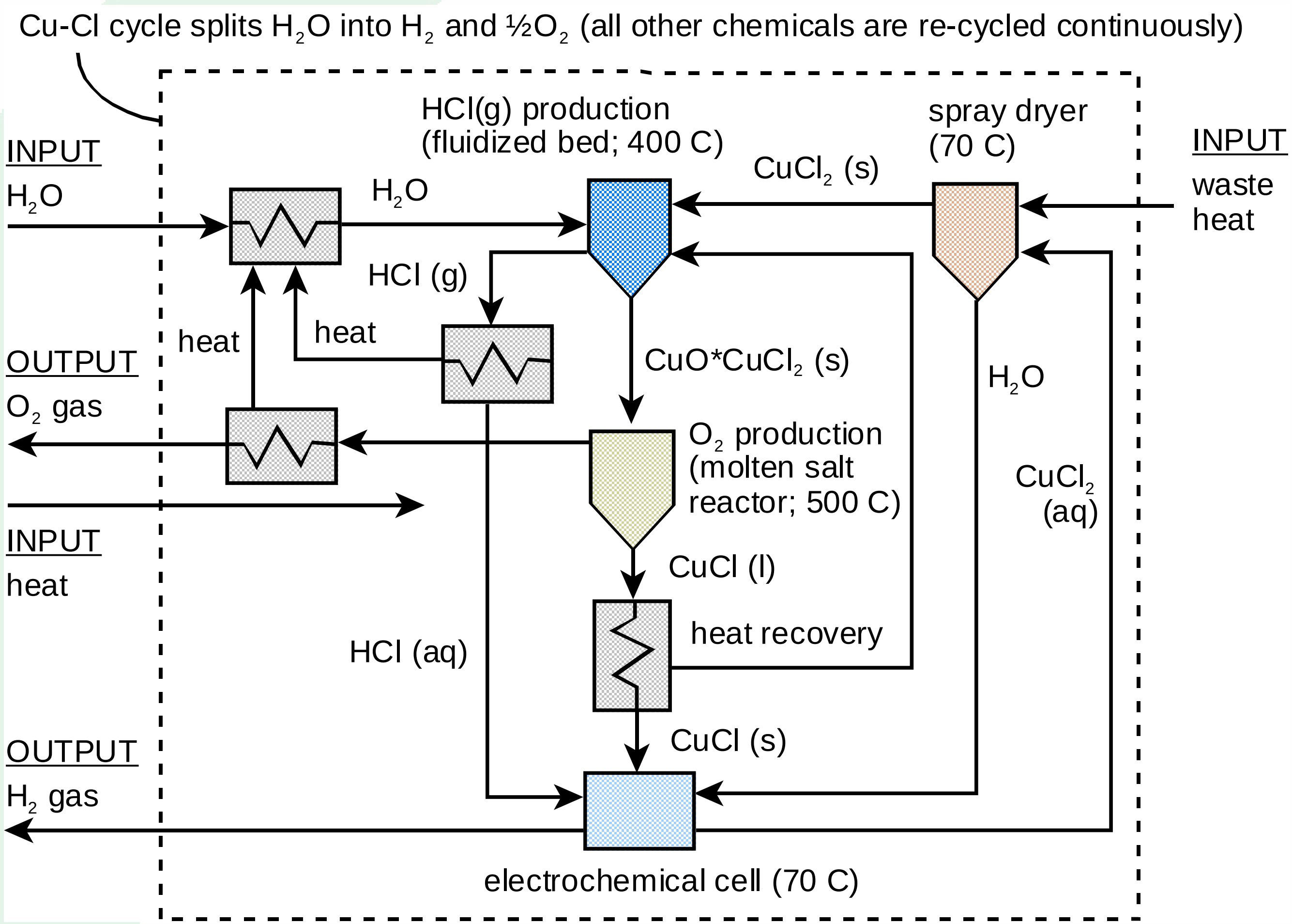
Table The main steps involved in the Copper-Chlorine Cycle.

Step		Reaction	Temperature Range (°C)
1	Electrolysis	$2CuCl_{(aq)}+2HCl_{(aq)} \rightarrow 2CuCl_{2\,(aq)}+H_{2(g)}$	~100
2	Separation/drying	$CuCl_{2(aq)} \rightarrow CuCl_{2(s)}$	< 100
3	Hydrolysis	$2CuCl_{2(s)} + H_2O_{(g)} \rightarrow CuOCuCl_{2(s)} + 2HCl_{(g)}$	350-400
4	Thermal decomposition	$CuOCuCl_{2(s)} \rightarrow 2CuCl_{(l)} + 1/2O_{2(g)}$	**450-530**



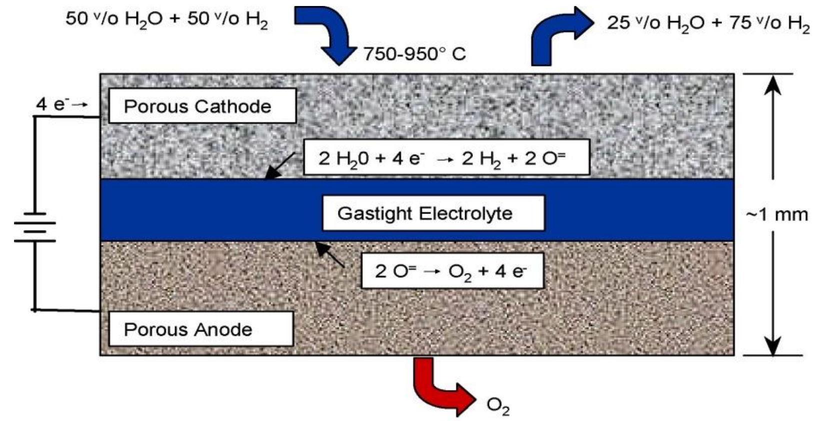
Canadian innovation/demonstration of this step spurred interest – now others following Canadian leadership

Copper-Chlorine Cycle



UNRESTRICTED / ILLIMITÉ

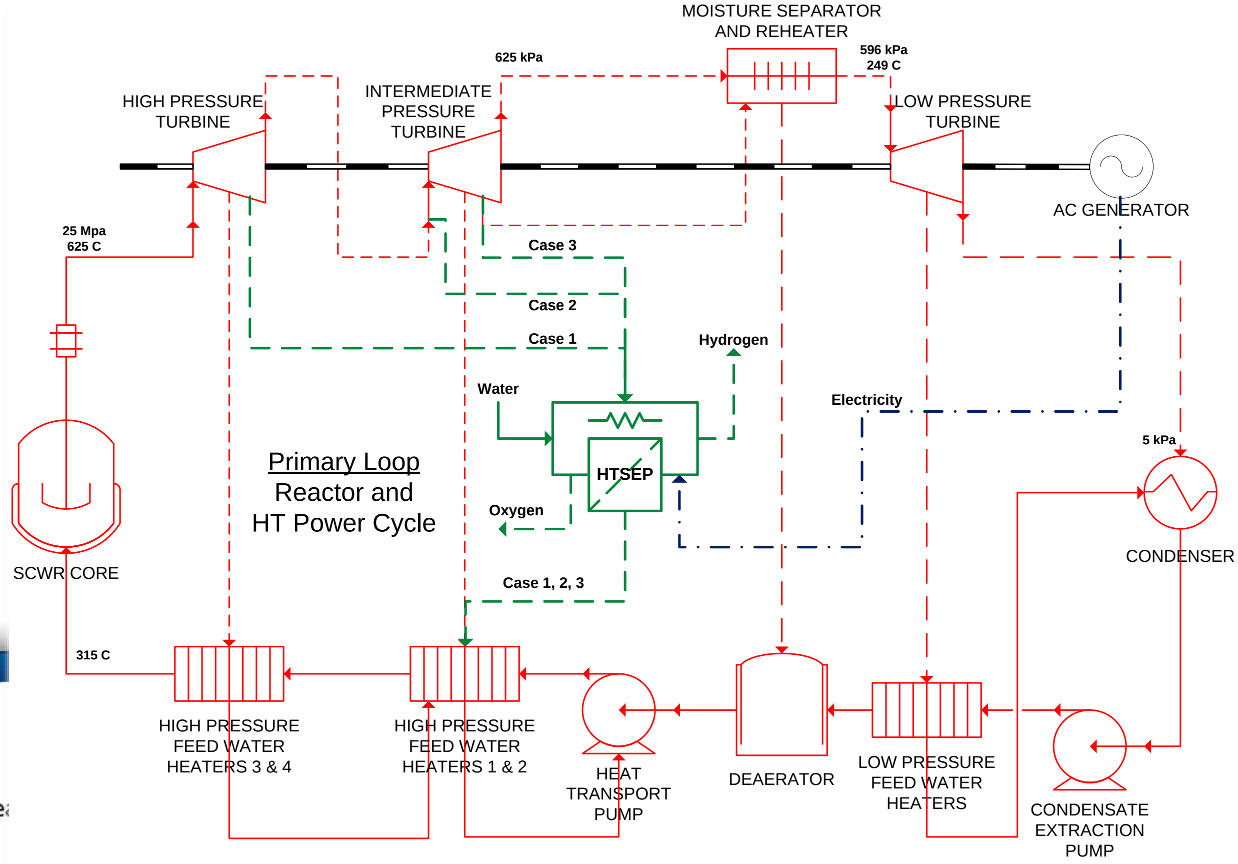
High Temperature Steam Electrolysis



- Canadian efforts:
  - ❑ Collaborated with INL
    - o Modelling Integration of HTSE with Nuclear
  - ❑ Materials development
    - –Focus on lowering the temperature of operation
    - –Testing of single cells
    - –Testing of a stack of small number of cells

Nuclear Hydrogen Production Simulation: HTSE integration with nuclear plants

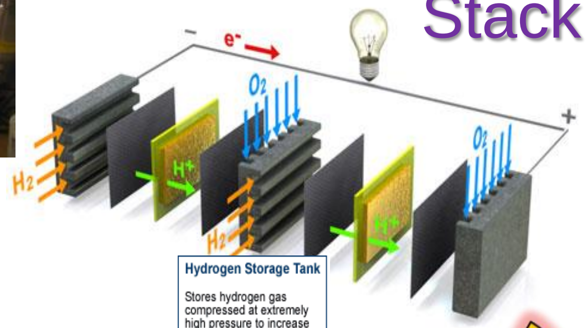
- ❑Simulates hydrogen production from Gen IV reactors
- ❑Optimizes electrolyser integration with reactor steam cycle
- ❑Enables assessment for feasibility of large-scale hydrogen production



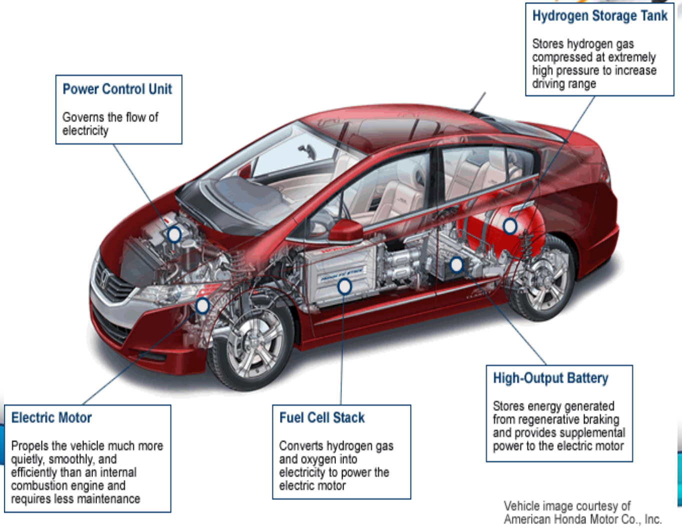
Canadian Nucle[...]
Laboratories

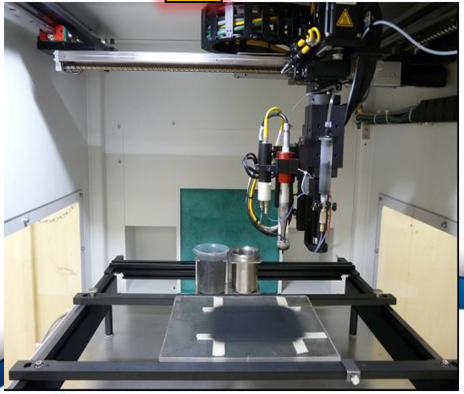
Fuel Cell Applications – CNL's catalyst technology

Stack



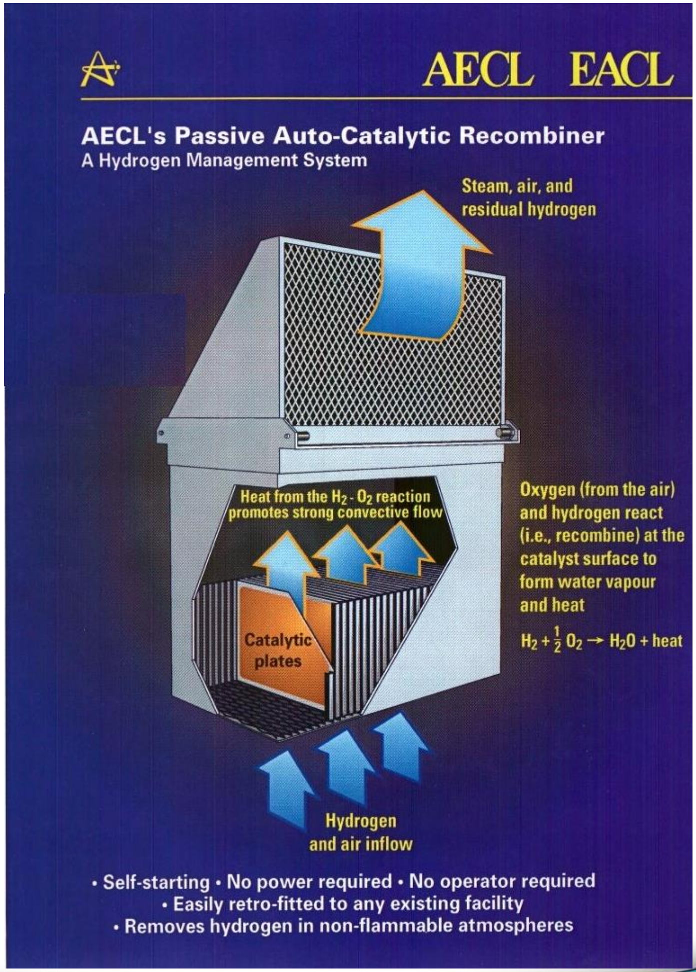
Fuel Cell Catalyst



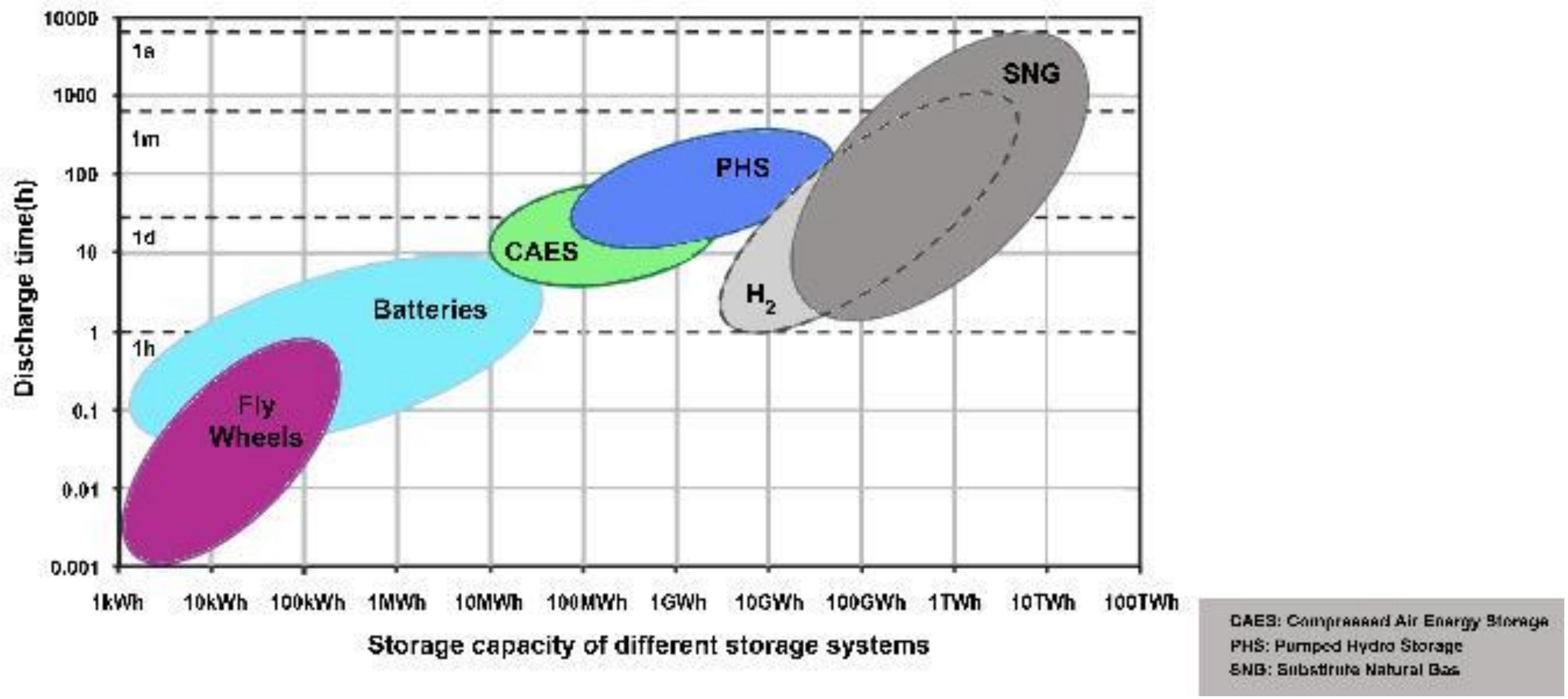


Passive Autocatalytic Recombiners (PARs) for H_2 Mitigation in Nuclear Reactor Containment

- Installed in CANDUs & PWRs
  - Licensed by Candu Energy Inc.
- 40% of French Reactors have Canadian PARs installed
- Potential for non-nuclear applications in hydrogen economy



Hydrogen Energy Storage: A Solution To the Renewable Energy Intermittency Problem



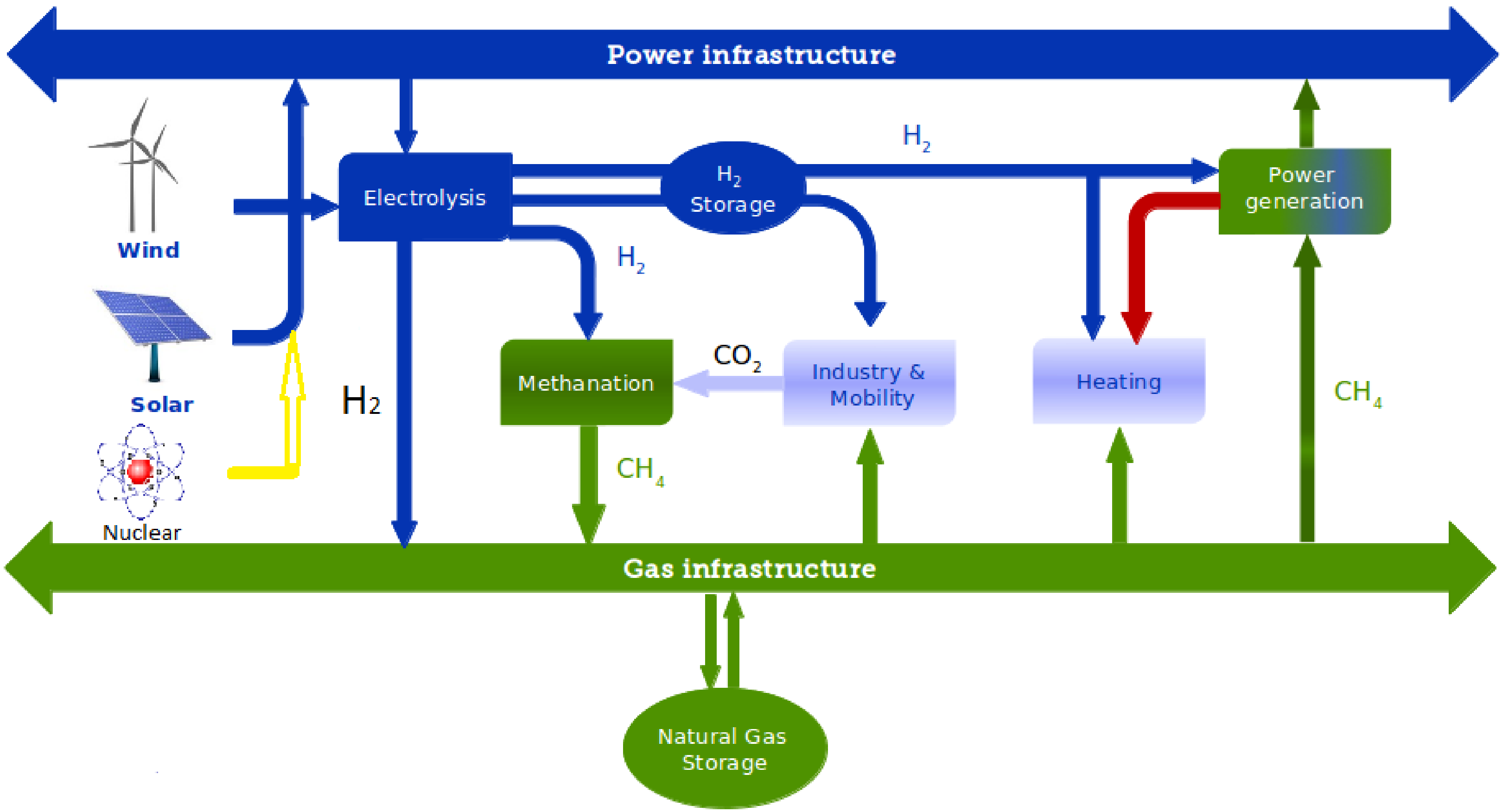
Hydrogen gas has the largest energy content of any fuel, making it a very good ‘medium’ for holding and distributing energy. With the ability to hold 120MJ/kg,

Hydrogen Storage

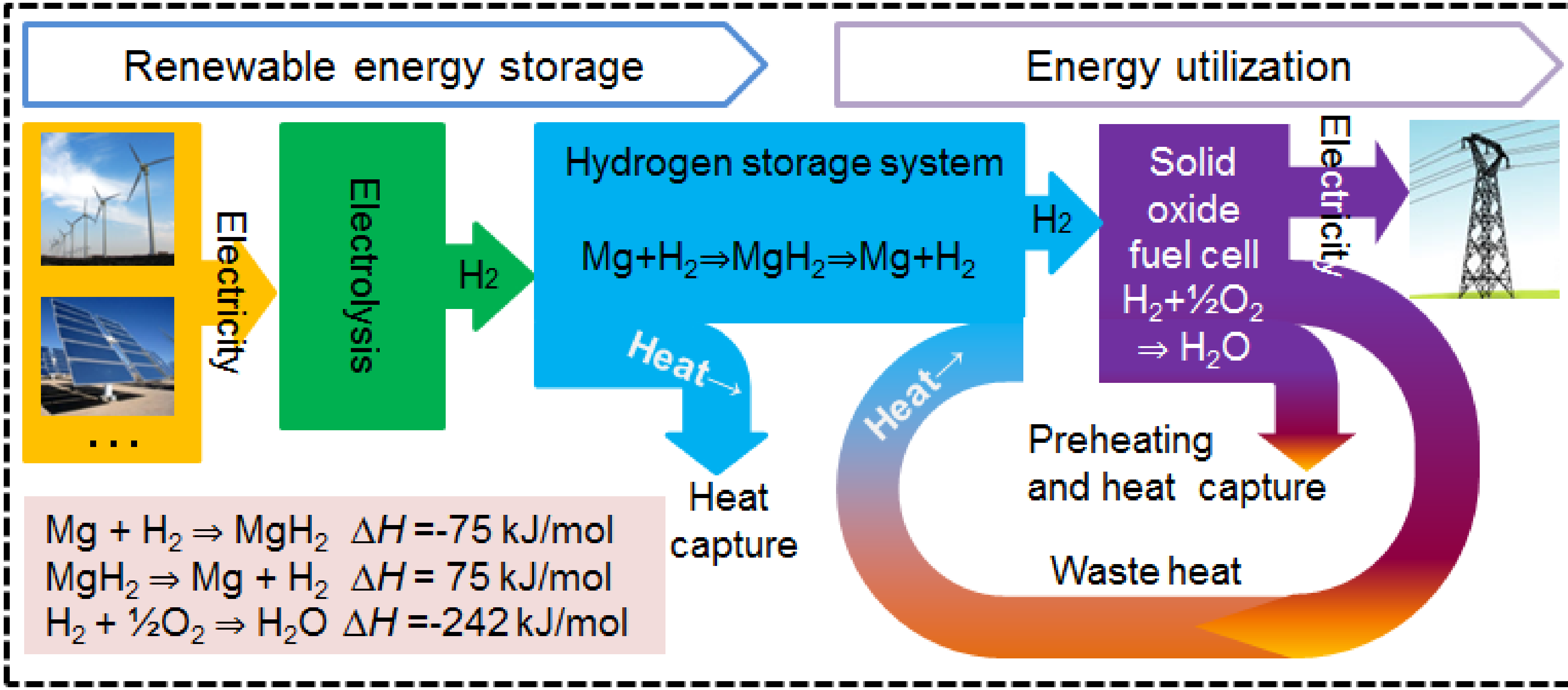
Unequalled Storage Density – Utility Scale
This example (actually a NG installation covering 4 acres) would contain 2.5 Gigawatt-hours of energy storage when applied to Hydrogen

-Tube trailer can deliver 4 to 6 MWh when used with fuel cell
-No leakage and no parasitic losses over time
-Minimum incremental storage capacity costs

Power-to-Gas

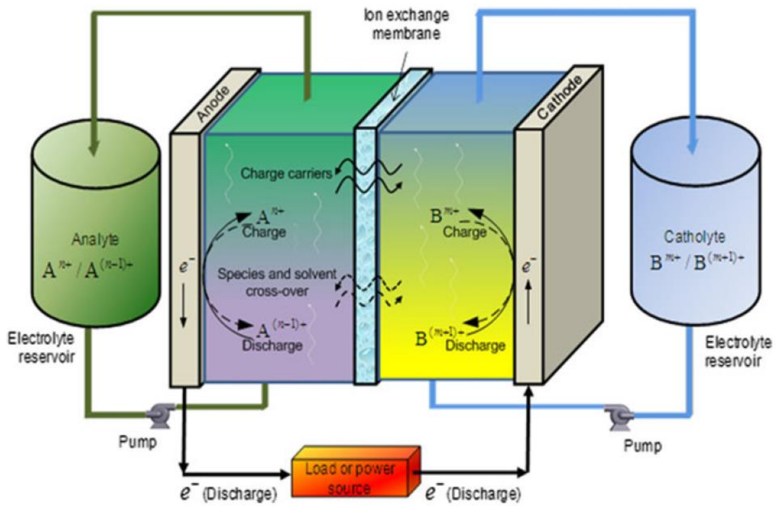

Power infrastructure
Wind
Solar
Nuclear
Electrolysis
H2
Storage
H2
H2
H2
Power
generation
Methanation
CO2
Industry &
Mobility
Heating
CH4
CH4
Gas infrastructure
Natural Gas
Storage

Hydrogen Storage on Metals



$Mg + H_2 \Rightarrow MgH_2 \quad \Delta H = -75$ kJ/mol
$MgH_2 \Rightarrow Mg + H_2 \quad \Delta H = 75$ kJ/mol
$H_2 + ½O_2 \Rightarrow H_2O \quad \Delta H = -242$ kJ/mol

Flow Battery as Energy Storage Medium



- Two closed loop systems (usually liquids)
- On discharge:
  - redox species in analyte solution undergo oxidation as they are pumped through anode
  - catholyte redox species undergo reduction at cathode
  - other charge carriers diffuse though central membrane to balance charge
  - electrons flow through external circuit
- On charge: electrochemical reactions are reversed

Energy Scene in Canada

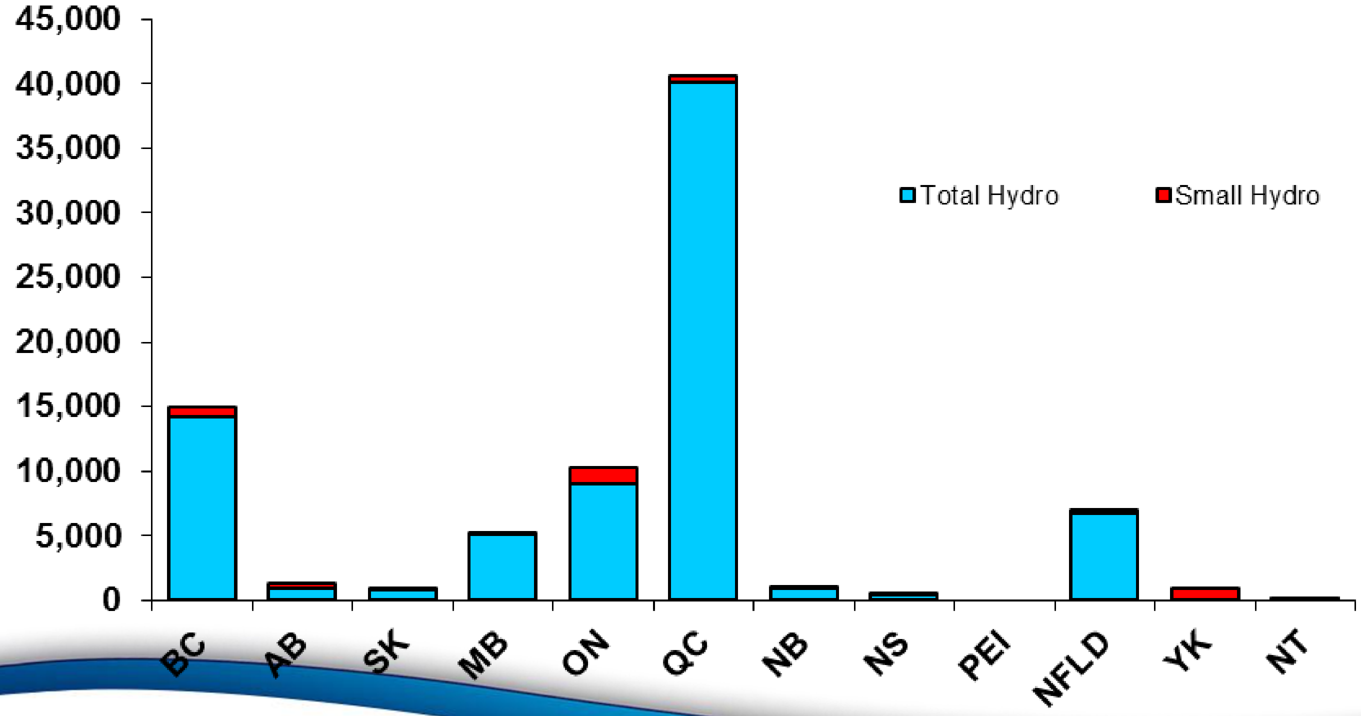
Nuclear in Canada

~18% electricity produced in Canada by CANDU
~50% electricity produced in Ontario by CANDU

Nuclear Station	Province	MWe	In service date	Operator
Pickering A	Ontario	4 x 515	1971-73	OPG
Pickering B	Ontario	4 x 516	1983-86	OPG
Darlington	Ontario	4 x 881	1990-93	OPG
Bruce A	Ontario	4 x 750	1977-79	Bruce Power
Bruce B	Ontario	4 x 860	1984-87	Bruce Power
Gentilly 2	Québec	1 x 635	1983	Hydro Québec
Point Lepreau	New Brunswick	1 x 635	1983	NB Power

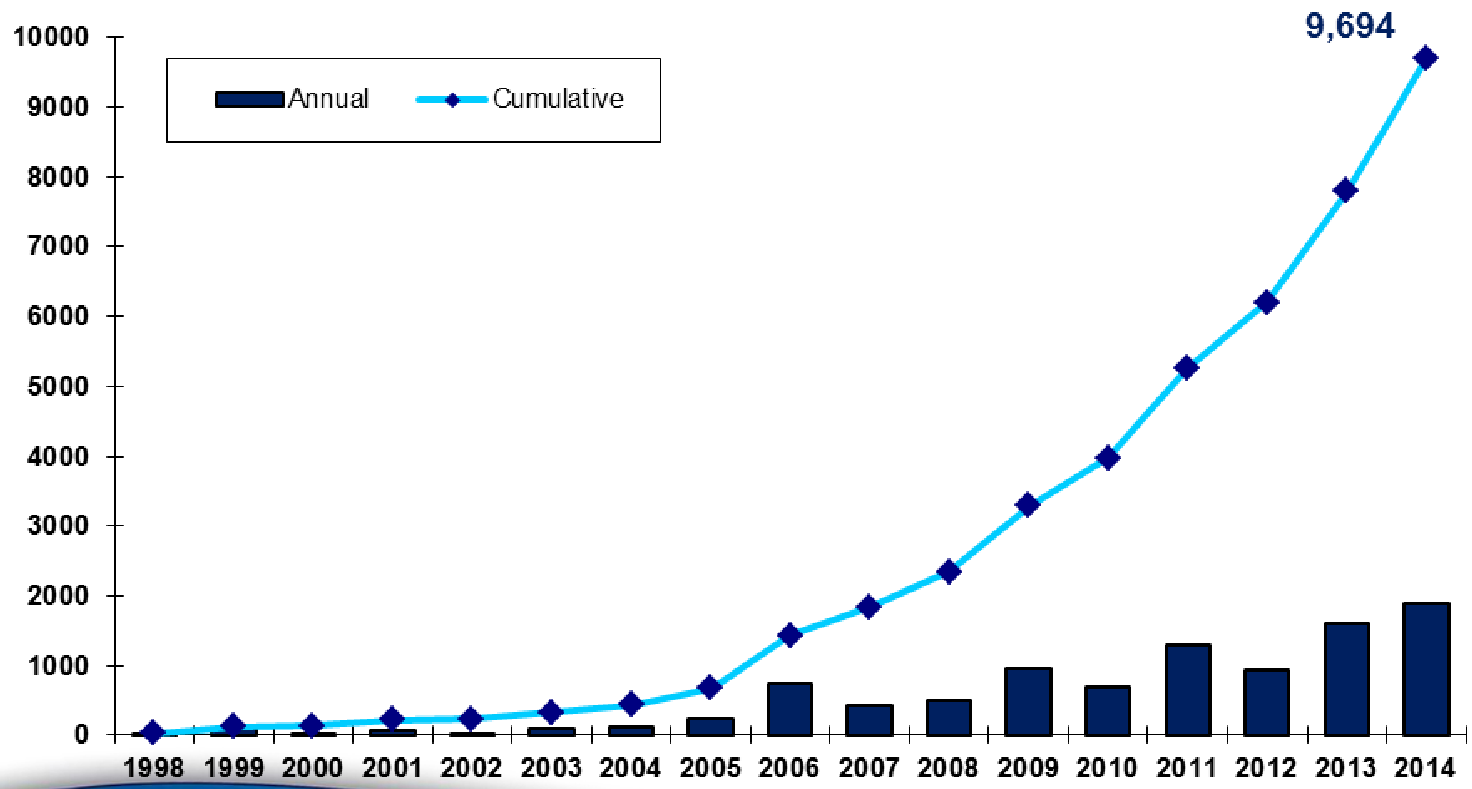
Installed Hydroelectric Capacity by Provinces (2014, in megawatts)

Moving water is the most important renewable energy source in Canada, providing 59.3 per cent of Canada's electricity generation. In fact, Canada is the second largest producer of hydroelectricity in the world.



Installed Wind Power Capacity in Canada (Megawatts)

Wind is the second most important renewable energy source in Canada. It accounts for 3.5 per cent of electricity generation in Canada.



Federal and Provincial Renewable Fuel Mandates (2014)

	Renewable Alternatives to Gasoline	**Renewable Alternatives to Diesel**
Federal	5 %	2 %
Provincial		
British Columbia	5 %	4 %
Alberta	5 %	2 %
Saskatchewan	7.5 %	2 %
Manitoba	8.5 %	2 %
Ontario	5 %	2 %
Quebec	5 % (target only)	--

Energy Scene in Canada - continued

- Canada, with its large landmass and diversified geography, has substantial renewable resources that can be used to produce energy; these resources include moving water, wind, biomass, solar, geothermal, and ocean energy.
- Canada is a world leader in the production and use of energy from renewable resources. Renewable energy sources currently provide about 18.9 per cent of Canada's total primary energy supply.
- Biomass is the third largest renewable source of Canada's electricity generation. Its share in Canada's electricity generation is 1.4 per cent.
- Wind and solar photovoltaic energy are the fastest growing sources of electricity in Canada.

A real commitment to decarbonization – Federal and Provincial Initiatives being announced

Thank you